AN OVERVIEW OF THE DOE TERRESTRIAL CRYSTALLINE
SOLAR CELL RESEARCH PROGRAM *

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There has been significant progress in the crystalline
solar cell area in the past two years that has rejuve-
nated interest in high efficiency devices for terres-
trial photovoltaic systems. The most significant deve-
lopments have been in the crystalline silicon cell area
but progress in the III-V area has also been recorded.
A review of terrestrial crystalline cell research is
presented along with a description of future research
directions.

INTRODUCTION

Photovoltaic systems are an attractive technology for
electric power generation. The United States Department of
Energy (DOE) has been pursuing PV research for over a decade with
the long term goal of lowering the cost of PV systems such that
they can be a cost effective option for utility applications. In
order to position PV for a utility market, it will be necessary
to reduce the cost of a PV system by a factor of 4 to 6 from
current systems (1). In order to meet these long term goals, DOE
is investigating two approaches for a cost effective PV device.
In the first approach, thin films of amorphous or semicrystalline
semiconductors which can be fabricated with low cost deposition
techniques are used. This technology features low material
costs; material costs are currently the most expensive component
in PV commercial flat-plate modules. The DOE effort in thin
films is managed by the Solar Energy Research Institute (SERI).
Industry has become interested in the thin film approach recently
and is making substantial investments in this new technology.
While the cost of the materials are low and the initial progress
is very promising, a significant challenge remains to improve the
performance of thin film cells to levels appropriate for utility
applications (>15%).

The second approach pursued by DOE is investigation of
crystalline cells. These cells are composed of high quality
materials and are capable of very high efficiencies. There is a
very large technological base for development of crystalline
cells. The concern with crystalline cells has always been

material costs. However, with concentrator collectors or with advanced sheet growth processes, the material cost issue may be circumvented while the performance advantage of crystalline cells is retained. Most of the DOE crystalline cell research has been recently consolidated at Sandia National Laboratories, including the research on crystalline silicon one-sun and concentrator cells and advanced materials concentrator cells. This paper will briefly review the present status of terrestrial crystalline cell research and give an outline of future research directions.

SILICON CELLS

Silicon cells have received the bulk of the research effort among crystalline cells. In order to improve the cost effectiveness of crystalline silicon cells, it will be necessary to reduce the material and processing costs and to improve the cell performance. Past work that was managed by the Jet Propulsion Laboratory emphasized reducing the material and processing costs through source material and advanced crystal growth research and through research into low cost processing techniques (metallizations, boule wafering, etc.). An excellent review of this work can be found in reference 2. Future work in this area will emphasize fundamental studies of advanced silicon crystal growth processes and characterization and control of defects. This work can later be can later be transferred to industry. The silicon materials research will probably involve more university participation and fewer large engineering development efforts. In an era of reduced budgets, it is felt that this approach will have the greatest impact on achieving program goals.

A novel approach to improving the cost effectiveness of current one-sun crystalline silicon cell technology has been recently developed by ENTECH, which manufactures concentrator modules. ENTECH has developed a prismatic coverglass which effectively removes the grid obscuration (6). With the larger current densities produced under concentrated illumination, concentrator cells have typically featured relatively expensive metallizations with a narrow linewidth, high aspect ratio, and low contact resistance. With the greater grid coverage that is possible with the prismatic coverglass, it becomes possible to use the low cost metallizations typical of one-sun cell technology for a low concentration module. An installed system cost near $6/Wp has been estimated for a small utility scale application (300 kW) with a 20X module, one-sun cells, and the prismatic coverglass (6). Figure 2 presents results for a polycrystalline silicon cell fabricated by Solarex with and without the coverglass. The grid obscuration in this case was 20%. It is evident from the results presented in Figure 2 that the coverglass was effective in eliminating the grid obscuration.

The second approach to cost effectivenss of crystalline silicon cells is to increase the efficiency of both one-sun and concentrator cells. Modelling at both Stanford and Purdue have indicated that efficiencies in excess of 30% are possible with thin, high resistivity silicon concentrator cells (3,4). These cell designs were thought to require long minority carrier life-

times that are only available in expensive float zone material. Recent modelling at Iowa State University indicates that high efficiencies should also be possible with minority carrier life-times typical of Czochralski or polycrystalline material if sufficient light trapping and surface passivation schemes are employed (5). These same calculations project efficiencies around 25% at one-sun (Figure 1). A common feature in all these modelling results is that the high efficiency silicon cells will need to be very thin and will use high resistivity material.

Progress in experimental high efficiency silicon devices has been very encouraging recently. Researchers at the University of New South Wales (UNSW) under Sandia sponsorship have recently fabricated low resistivity 0.1 and 0.2 ohm-cm silicon concentrator cells that achieved 24.7% at 50X to 100X (7). (All measurements reported in this paper were made under an AM1.5 spectrum, with the irradiance at one-sun (1X) equal to 100 mW/cm^2.) Two improve-ments have been incorporated into these cells. The first improvement is the use of a passivated surface with reduced contact area in order to minimize recombination at the surface of the cell. The second improvement has been optimization of the optical properties of the front surface in order to minimize reflectance from both the active area and the grid lines. The surface has been anisotropically etched to form microgrooves that reduce the surface reflectance. The grid lines are defined at approximately a 45 degree angle with respect to the grooves so that light specularly reflected from the grids can be absorbed at the adjacent surface of the groove. The improved front surface design is illustrated in Figure 3 along with cell performance data. This cell uses essentially the same structure as commer-cial silicon concentrator cells (contacts on both the front and back surfaces with the back surface fully metallized) and could be incorporated into concentrator modules relatively easily. Using a similar approach for one-sun silicon cells, the researchers at UNSW have also achieved an efficiency of 21% and 19% at one-sun for cells fabricated in float-zone silicon and in solar-grade Czochralski silicon (8).

In another remarkable achievement, researchers at Stanford University have achieved 27.7% at 100X and 22.2% at one-sun with an unconventional cell structure (8). The new cell structure (see Figure 4) starts with a high-resistivity float zone silicon substrate. The substrate is first chemically etched to the desired thickness of about 100 microns. Both the n- and p-type diffusions are then made on the back surface. The area of the diffusions and of the metal/silicon contact area is minimized in order to reduce the recombination associated with the heavily doped regions and with the contacts. It is also very important to incorporate light trapping in order to maximize absorption of light in the thin silicon cell and to passivate the surfaces in order to minimize surface recombination. The high efficiency is due to both the high current densities (Jsc>40 mA/cm^2) and the high voltages (Voc>680 mV at 1X) achieved in this cell. The Stanford researchers project that efficiencies of 29% under concentrated sunlight are possible using the present design with reduction of the cell reflectance and grid resistance.

Figure 5 shows the progress of crystalline silicon cell efficiencies over the past 10 years. The increase in silicon cell performance has been due to both improvements in processing and improved cell designs. Future advanced silicon crystalline cells will be thin (<100 microns) and will include light trapping, passivated surfaces, and optimized emitter structures. Other areas that will also need to be addressed include hetero-junction contacts to minimize contact recombination and issues regarding the module readiness (reliability, stability, mechanical mounting, etc.) of these advanced cells. Silicon cells with efficiencies in excess of 24% and 30% at one-sun and under concentration appear to be quite achievable.

ADVANCED MATERIAL CONCENTRATOR CELLS

By advanced materials, we refer to crystalline III-V compound semiconductors. These materials have been used for elecro-optical devices for over a decade due to their superior electro-optical properties compared to silicon. It is no surprise that these same qualities make these materials very effective for solar cells. The materials for these cells are significantly more expensive than for silicon cells, so that these cells can only be cost effective if their performance can be significantly increased over the projected silicon cell performance of 30% and if they can be operated at higher concentrations (>500X). Consequently, the long term goal of this task is to develop a highly efficient (>35%) multijunction (MJ) concentrator cell for operation at high concentrations (>500X).

An integral part of MJ cell development is to first develop optimized single-junction devices. The higher efficiencies of MJ cells compared to single-junction devices comes from the more efficient use of the broad solar spectrum. However, the projected high efficiencies can only be attained if the properties of each subcell in the MJ cell are nearly optimal. The latter requirement implies that the performance of a single-junction cell be well understood before an MJ cell can be optimized.

The high efficiencies that have been achieved with single-junction III-V solar cells despite the relative immaturity and modest support of this technology demonstrates the performance potential of III-V solar cells. Two years ago, Varian fabricated GaAs concentrator cells that achieved 26% at 700X (9). This cell had the highest reported efficiency of any photovoltaic device until the recent silicon cell results reported by Stanford. It should also be noted that on an active area basis, these cells are more efficient than the new silicon cells. GaAs solar cells are still the most efficient PV devices reported to date for one-sun illumination with an efficiency of 23% (10). Projections for GaAs cells also predict very high efficiencies for an optimized cell. By combining the best parameters (Voc, Jsc, and FF) observed on different GaAs cells, Fan has projected an efficiency of 26% for GaAs at one-sun (11). Similarly, the researchers at Purdue University project efficiencies near 34% for a GaAs cell operating at 500X using realistic values for the material parameters with a detailed computer modelling code (12).

Another demonstration of the high performance potential of III-V cells is the recent set of results with InGaAs concentrator cells. These cells were also fabricated by Varian and were developed as part of monolithic MJ work funded by SERI and by NASA. These InGaAs cells have a bandgap of 1.15 eV, which is close enough to silicon to allow a direct comparison of the relative merits of III-V and silicon cell technologies. The InGaAs concentrator cell achieved 24.4% at 400X despite a poor Jsc at one-sun of 31 mA/cm^2 (13). An efficiency in excess of 30% is projected for these cells if the Jsc can be improved to levels already demonstrated for silicon cells (36 to 40 mA/cm^2). The high performance of these cells was due to their high Voc, which under concentration is over 100 mV higher than the best silicon concentrator cell voltages (Figure 7).

In order to further improve single-junction GaAs and other III-V cells, it will be necessary to improve the short-circuit current density (Jsc). Unlike silicon cells, the open-circuit voltage (Voc) of III-V cells have traditionally been very good but have had a poor Jsc. For example, a compilation of reported Voc's for various III-V cells with bandgaps between 1.15 eV and 2.0 eV shows that the Voc is within 10% of the fundamental voltage limit imposed by radiative recombination (13). Some of the improvement in Jsc will come from techniques that remove some of the grid obscuration, such as the prismatic coverglass or use of a microgrooved surface. Some of the improvement of Jsc will also need to come from better material quality and device optimization since the peak internal quantum efficiency is generally below 95% and have poor response at short wavelengths (Figure 6). As was found to be very useful for silicon cell development, sophisticated models and advanced measurements are needed to help guide the device development.

The two approaches to achieving a high efficiency MJ cell are the monolithic MJ (MMJ) and the mechanically stacked MJ (MSMJ) cells. Research into MMJ cells for terrestrial applications is managed through SERI and has been reviewed at this conference in previous years (14). Sandia has been investigating MSMJ cells whose progress has been promising. A GaAs/silicon MSMJ cell was assembled at Sandia with the component GaAs and silicon cells fabricated by Varian and Applied Solar Energy Corporation, respectively. The GaAs cell had grids on the front and back surfaces in order to allow light transmission to the silicon bottom cell. The cells were not otherwise optimized for stacked cell operation. The GaAs/silicon MSMJ cell achieved 26.6% at 300X when the subcells were operated independently (Figure 8), which briefly held the record efficiency until the recent silicon cell results (15). We have estimated that this approach can obtain about 5% from the silicon cell and thereby over 30% for the GaAs/silicon MSMJ cell under concentration (16). Even higher performance is projected for an MSMJ cell using an optimized bandgap combination. Sandia is supporting development of a wide bandgap (1.75 eV) cell for stacking on top of a silicon cell and of a narrow bandgap (0.7 eV) cell for stacking underneath a GaAs cell.

Another important development in MJ cells has been the examination of new electrical configurations other than the series-connected configuration for MJ cells. In particular, a new voltage-matched configuration has been proposed by researchers at Chevron for MSMJ cells (18). Voltage-matched configurations can also be used with MMJ cells (17). The voltage-matched configuration connects the cells in parallel so that the bandgap selection criteria becomes matched voltages rather than matched currents as in series-connected MJ cells. This configuration has been recently modelled at Sandia and several advantages were found for the voltage-matched configuration (17). These advantages include wider selection of bandgaps for the component cells, less sensitivity to spectral variations inherent in terrestrial spectra, structures that avoid the difficult transparent ohmic interconnect required in series-connected MMJ cells, and possibly better radiation resistance for space applications. It is expected that the advantages of a voltage-matched configuration will make realization of an efficient MJ cell easier.

SUMMARY

We have reviewed recent developments and presented an outline of the research topics in the DOE terrestrial crystalline cell program. With an integrated program of material and device research, we feel that crystalline PV systems can become an important renewable energy source for the United States.

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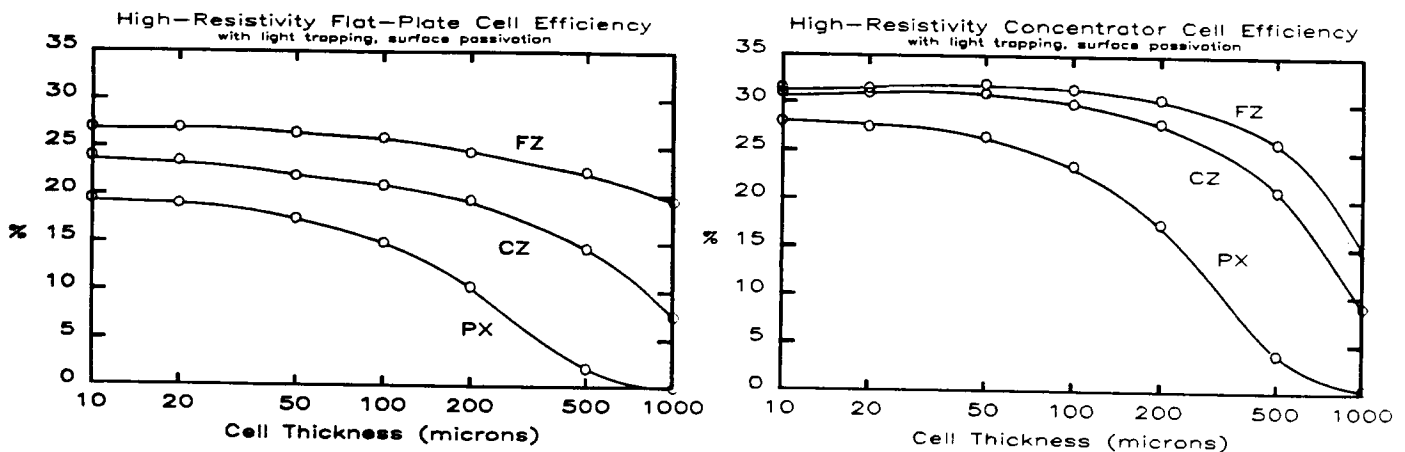
Figure 1.   Iowa State University cell efficiency modelling
results incorporating light trapping and surface passivation for
minority carrier lifetimes typical of float-zone (FZ),
Czochralski (CZ), and polycrystalline (PX) silicon.   Results for
one-sun and at 100X are presented.

ONE SUN PERFORMANCE

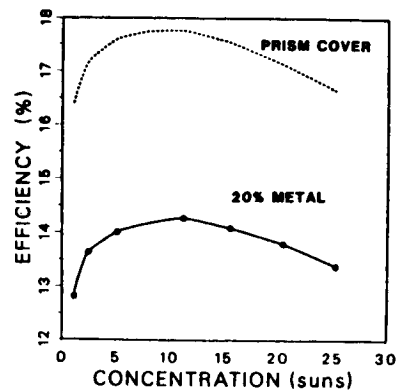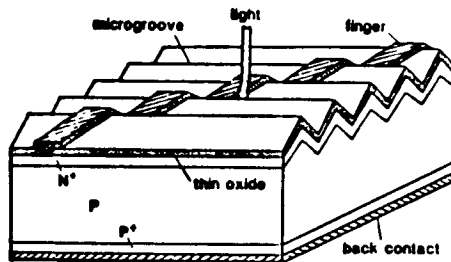|	SOLAREX (POLY SI)	ARCO (CZ)
$A(CM^2)$	39.5	39.4
V_{OC} (V)	.572	.570
FF	.760	.74
I_{SC} (A)	1.18	.565
I_{SC}^* (A)	1.42	1.38

*WITH PRISM COVER

SOLAREX POLY Si

Figure 2.   Results for silicon cells fabricated with one-sun silicon cell technology under low concentrations.   The obscuration of the 20% metal grid coverage is removed with a prismatic coverglass.

ONE SUN PERFORMANCE

	.1 Ω-CM	.2 Ω-CM
A (CM2)	.09	.09
Jsc (MA/CM^2)	38.8	40.2
Voc (V)	.663	.651
FF	.836	.825
η(%)	21.5	21.6
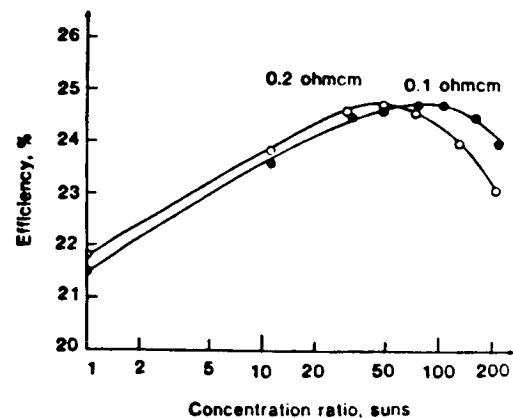
Figure 3.   University of New South Wales low-resistivity silicon concentrator cell test results and cell structure.

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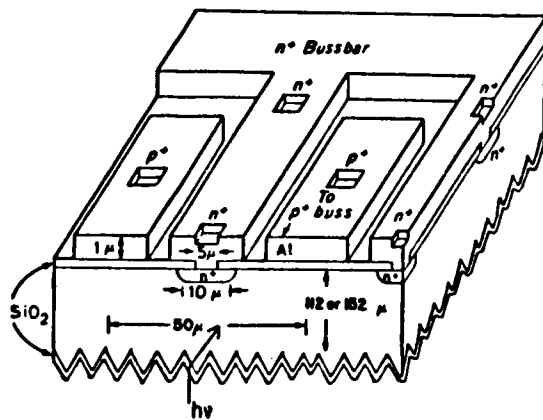
CELL PERFORMANCE

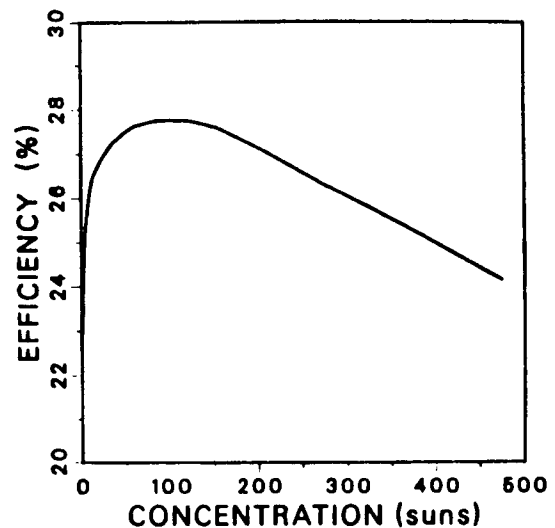|	1X	100X
AREA (CM^2)	.15	.15
J_{SC} (A/CM^2)	.0415	4.15
V_{OC}^* (V)	.682	.809
FF	.785	.826
η (%)	22.2	27.7

Figure 4. Test results and cell structure for Stanford's Point Contact Concentrator (PCC) cell.

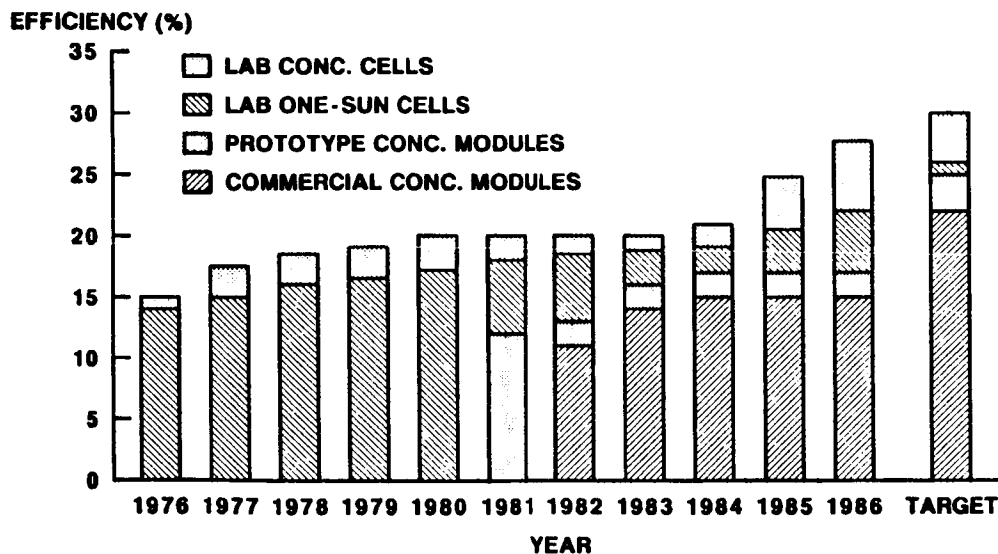# PHOTOVOLTAIC EFFICIENCY PROGRESS IN SILICON

Figure 5. History of silicon cell and module efficiency improvements. All efficiencies measured at Sandia under standard test conditions.
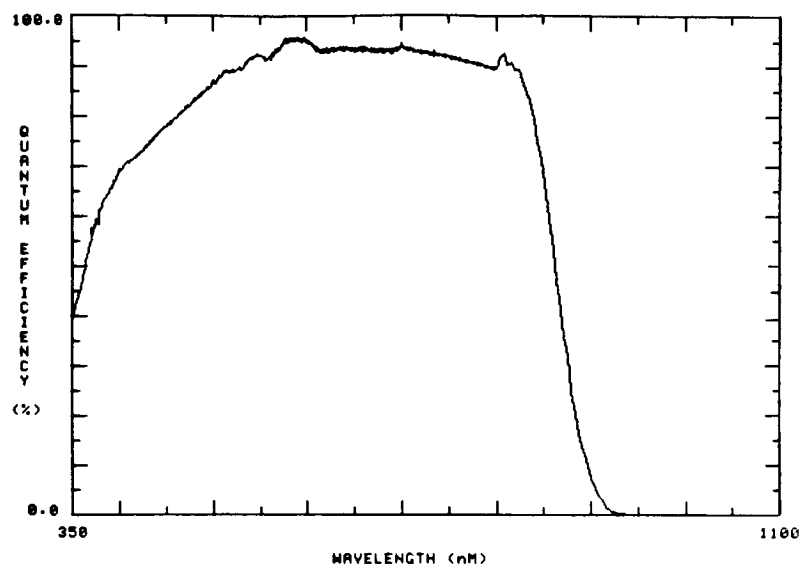
Figure 6. A plot of the internal quantum efficiency for a high efficiency GaAs concentrator cell fabricated by Varian.

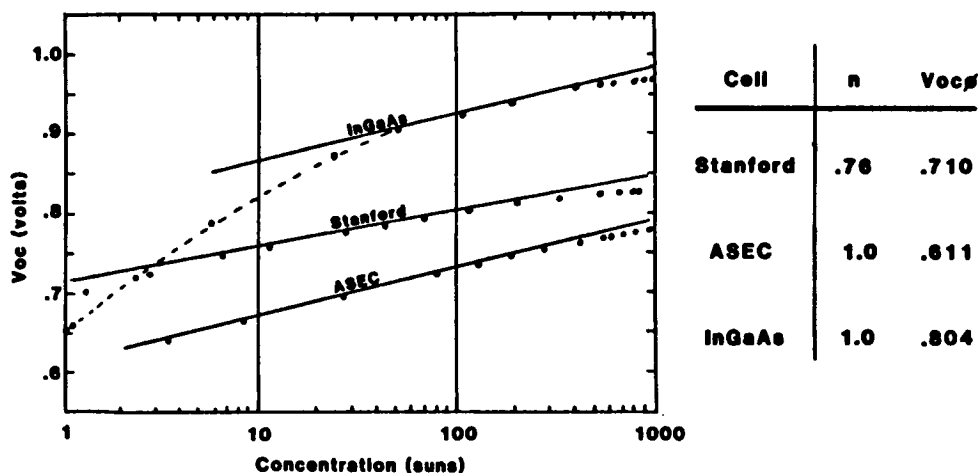| Cell	n	Voc∅
Stanford	.76	.710
ASEC	1.0	.611
InGaAs	1.0	.804

Figure 7. Voc versus irradiance for an InGaAs cell, an advanced silicon cell (Stanford's PCC Cell), and a commercial low-resistivity concentrator cell (ASEC). The data are plotted as points and the solid lines are a fit of the data to the diode equation. The parameters for the fit are given in the adjacent table.
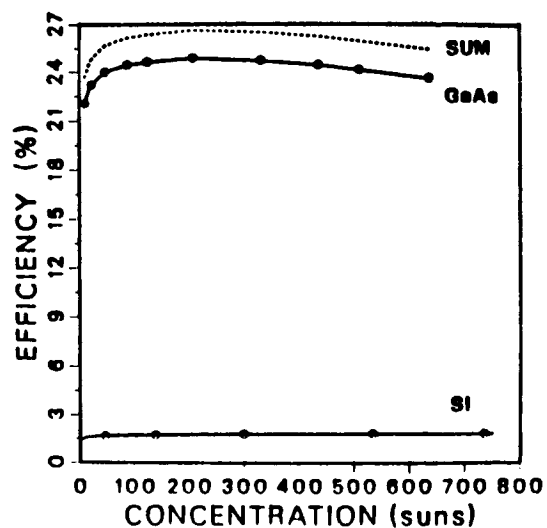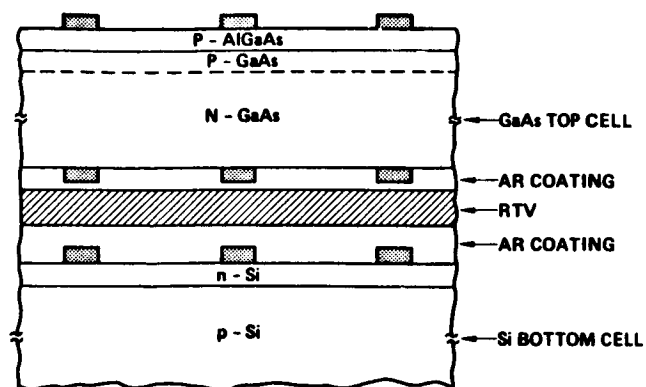
Figure 8. Test results for a MSMJ cell assembled by Sandia using component cells fabricated by Varian (GaAs top cell) and by ASEC (silicon bottom cell).

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